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WASHINGTON, D.C. 20546

REPLY TO
ATTN OF: GP

October 15, 1970

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General
Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned
U.S. Patents in STAR

In accordance with the procedures contained in the Code GP to Code USI memorandum on this subject, dated June 8, 1970, the attached NASA-owned U.S. patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No.	:	3,300,717
Corporate Source	:	Space Technology Labs
Supplementary Corporate Source	:	
NASA Patent Case No.	:	XLE-00821

G Parker

Gayle Parker

Enclosure:
Copy of Patent

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"ID APPARATUS FOR MEASURING POTENTIALS IN PLASMAS

Filed Oct. 5, 1962

Fig. 1

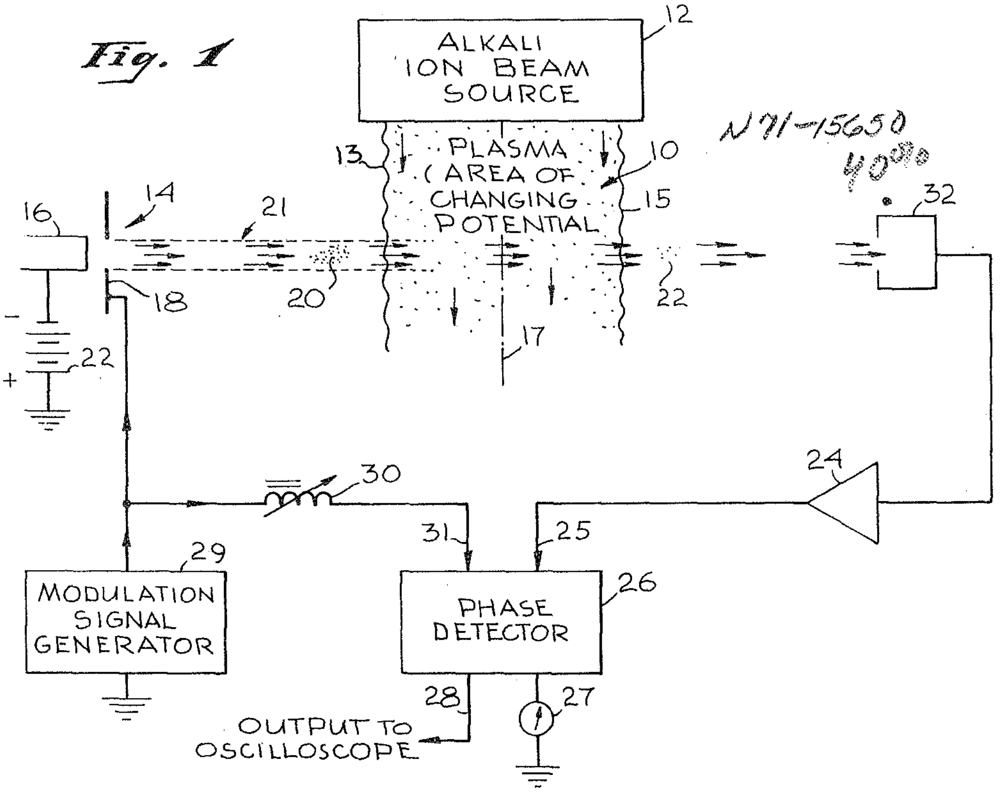

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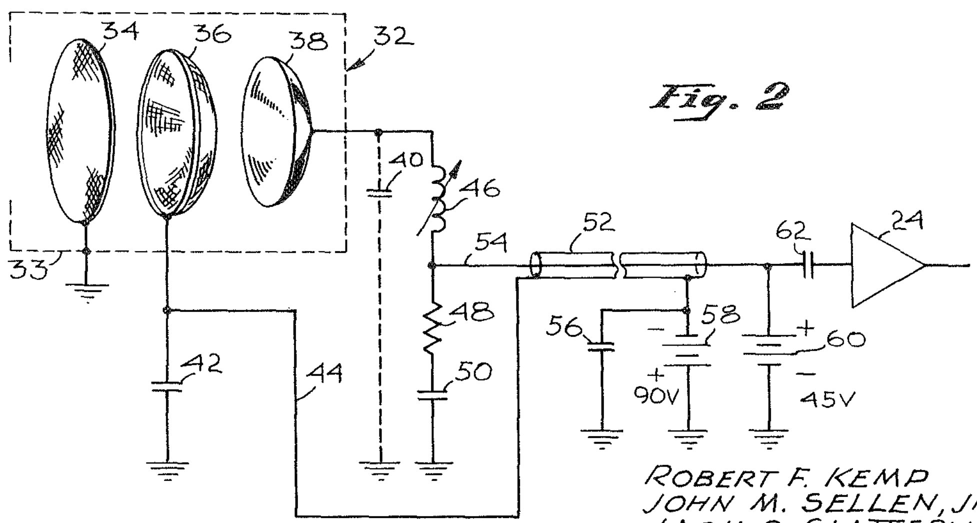
Fig. 2



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3,300,717

METHOD AND APPARATUS FOR MEASURING POTENTIALS IN PLASMAS

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9 Claims. (Cl. 324—72)

Our invention relates to the measurement of potential levels and potential variations in plasmas, and more particularly to methods and apparatus for measuring the electric potential at selected points in a beam or stream of ionized particles relative to the potential of the ion source or the potential of other appurtenances of the system. In its broader aspects our invention is not limited to measuring potential variations in plasmas, but may be used for measuring such variations in any body of dilute gas or near vacuum through which an electron beam can be projected. One method and apparatus of the class to which the present invention relates is described in a technical paper entitled "Advanced Ion Beam Diagnostic Techniques," American Rocket Society, Space Flight Report to the Nation, New York Coliseum, October 9, 1961.

The present invention finds one application in space vehicles of the general type discussed in an article entitled "Electrostatic Propulsion," Proceedings of the IRE, volume 48, No. 4, April 1960, pages 477 through 491. A further and perhaps more detailed description of ionic propulsion systems which provides a background from which the present invention proceeds may be found in Space Technology, edited by Howard Seifert, John Wiley and Sons, Inc., New York (1959).

In vehicles employing ionic propulsion, as described in the above-mentioned Space Technology publication, it is current practice to generate an efflux of propellant ions by contact ionization on the surface of a tungsten emitter and to thereafter accelerate the ionized particles by means of electrostatic fields. After acceleration it is necessary to neutralize the exhaust stream by addition of electrons. One method of neutralization uses a hot wire tungsten filament stretched across the ion beam immediately downstream from the accelerating electrodes. To maintain adequate neutralization of the plasma exhaust stream and to determine the optimum potential of the neutralizing filament it is necessary to provide methods and apparatus for monitoring the electrostatic potential of at least some portions of the exhaust stream relative to the propulsion engine. In order to impart momentum to spacecraft, the ionic exhaust beam must have its interior space charge neutralized by addition to the beam of a current of electrons equal to the ion current. The resulting engine exhaust beam is a dilute plasma having a density of the order of 10^{10} particles per cubic centimeter. Besides being dilute, the neutralized ion beam has other unique properties. It is characterized by ordered ion motion which is accompanied by a more or less disordered motion of high temperature electrons. The temperature of the neutralizing electrons relates to the perveance of the neutralizing electron source (i.e., the transversely extending filament) to the beam, and hence relates to the potential to which the plasma must rise with respect to the neutralizing source in order to extract the required electron current from the source of neutralizing electrons. Accurate measurement of this potential presents a number of problems. Prior potential measuring methods using metal probes and the like may perturb the very potential distribution which the apparatus is attempting to measure. With most prior art devices and methods for

plasma potential measurement it is difficult to know with certainty that the measuring instrument is not upsetting the conditions which are being measured. The foregoing problem is compounded in the case where the ion engine is operated or tested by repetitively pulsing the ion beam generator into emission. The prior methods of measurement are inadequate to detect and measure high frequency events in the ion such as axially distributed potential transients having durations of the order of one microsecond. The method and apparatus of the present invention not only overcomes the basic difficulty of measuring without perturbing the ion beam, but also enables detection and measurement of intraplasma potential transients having durations of less than one microsecond.

Having in mind the aforementioned limitations of prior art measuring methods and apparatus, it is a primary object of our invention to provide an improved method and apparatus for measuring potential levels in a neutralized plasma or partially neutralized stream of electrostatically charged particles.

Another object of our invention is to provide an improved method of measuring potential gradients or potential fluctuations in a stream of ionized particles.

A different object of our invention is to provide an ionic propulsion system having improved means for monitoring and controlling the electrical neutrality and stability of the ion beam exhaust from the engine.

An additional object of our invention is to provide an improved apparatus of the type described which is capable of detecting high frequency and transient plasma potential variations having time durations of the order of one microsecond.

The foregoing and other objects of our invention will be more apparent and better understood from the following description taken with the accompanying drawing, throughout which like reference characters indicate like parts, which drawing forms a part of this application and in which:

FIG. 1 is a diagrammatic illustration, partially in block diagram form, of one embodiment of a method and an apparatus in accordance with the invention; and

FIG. 2 is a schematic diagram illustrating in further detail a portion of the apparatus of FIG. 1.

As shown in FIG. 1, an electrostatic propulsion space vehicle normally comprises an alkali ion beam source 12 which emits a high velocity stream or beam of ionized particles. Normally and preferably, the ion beam is post-acceleration neutralized by addition of a quantity of free electrons equal to the charge density of the ionized particles. The ion beam source 12 may be, for example, an apparatus of the type which is disclosed and claimed in co-pending United States patent application Serial No. 203,200, filed June 18, 1962, which application is assigned to the same assignee as that of the present application. Accordingly, it is unnecessary to further describe the ion beam source 12 except to note that it produces a broad beam of neutralized plasma which travels downwardly along the axis 17 as shown in FIG. 1 and which is bounded, as indicated by lines 13 and 15.

As stated heretofore, the internal potential of the plasma in the ion beam may vary from point to point along the direction of the axis 17. Optimum operation of the ion engine 12 in a space vehicle requires that the ion beam be completely neutralized. To determine the operative parameters of the engine which produce complete neutralization, it is necessary to provide means for measuring the potential within the plasma beam and, particularly in the case where the ion engine operates in a pulsatory mode it is necessary to detect and measure the character and almplitude of transient variations in the plasma potential. The method and apparatus of the present invention accomplishes such measurement by observing variations in the intraplasma transit time of the electrons of an electron beam 21 which is directed transversely through the neutralized ion beam from the boundary 13 to the boundary 15. As shown in FIG. 1, the transversely directed electron beam 21 is generated by a conventional electron gun 14 which comprises a cathode structure 16 and a centrally apertured accelerating electrode 18. To provide acceleration of the electron beam, the cathode structure 16 is negatively biased to about 1000 volts by means of a voltage source 22 connected between the cathode 16 and ground or a point of reference potential. The accelerating electrode 18 is maintained at direct current ground potential and is further connected to a modulation signal generator 29 which applies an alternating current modulation signal to the accelerating electrode 18 to modulate the beam intensity. The intensity modulated electron beam is directed along a beam path 21 and through the plasma beam 10 into a beam collector 32 at the far side of the plasma beam. When the ion source 12 is inactive so that the plasma beam 10 is absent, the potential everywhere in the region between the electron gun 14 and the beam collector 32 is zero. Under such conditions the beam electrons have a fixed transit time from the gun 14 to the collector 32. When the alkali ion plasma is present in the region between the boundaries 13 and 15, elevation of the potential in the region (due to the positively charged plasma particles) causes the beam electrons 20 to travel at a different speed and, hence their transit time is measurably altered. That is, electric fields in the plasma which are parallel to the direction of the cathode ray electron beam will accelerate the beam electrons and therefore produce a variation in the transit time of the beam electrons. When the electron beam is modulated at a high frequency, the phase of the modulation signal on the exiting electrons 22 may be compared with the phase of the modulation on the injected electrons 20 to measure the transit time of the beam electrons. Generally it is not necessary or particularly desirable to measure the absolute transit time. Accordingly in preferred embodiments the appurtenant circuits are arranged to detect and measure time variations in the transit time and not the absolute transit time. As shown in FIG. 1, after exiting from the plasma the electrons 22 are received by a collector 32 which will be described in further detail hereinafter. The signal leaving the collector 32 is preamplified for an amplifier 24 which preferably is tuned to the same frequency as that of the modulation signal generator 29. Thus, collector 32 and amplifier 24 serve to detect and amplify a signal representative of the intensity modulation of the exiting electron beam. In a preferred embodiment of our invention which has been constructed and successfuly utilized in the investigation of plasma phenomena, the modulation signal generator 29 provides a 30 megacycle modulation signal and the amplifier 24 comprises a conventional 30 megacycle IF strip. From the amplifier 24 the signal is fed by way of input line 25 to a phase detector 26 where its phase is measured relative to a reference signal. In a preferred embodiment, reference signal is derived from the 30 megacycle signal generator 29 and applied to the phase detector 26 by way of a variable delay line 30 and a second input line 31. The variable delay line 30 is provided in the reference signal circuit to enable adjustment of the relative phase between the reference signal and the signal from collector 32.

The phase detector circuit 26 may be any one of various circuits known in the art. We have found that a phase detector which is immune to input signal amplitude variations is particularly advantageous for the measuring method of the present invention. A complete description of a phase detector circuit which has been used successfully in one embodiment of the present invention may be found in a paper by J. C. Slattery and R. F. Kemp entitled "A Plasma Potential Probe Using Electron Time-of-Flight," The Review of Scientific Instruments, volume 33, No. 4 (April 1962), pages 463–467.

In operation, the system illustrated in FIG. 1 measures the phase differential between the 30 megacycle signal from collector 32 and the reference signal from generator 29 and provides an output from the phase detector 26 indicative of the relative transit time required for the beam electrons 20 to traverse the plasma area between the boundaries 13 and 15. The relative transit time should be understood as meaning the transit time during "plasma present" conditions as compared to or relative to the "no plasma" transit time when the ion emitter 12 is quiescent. Since the transit time of the electrons depends on the potential in the plasma region, it follows that the phase detector output signal is indicative of the instantaneous plasma potential and may be used to detect and measure transient variations in the plasma potential. A phase indicative meter 27 is provided at a first output of the phase detector. A second output signal is provided by way of line 28 for application to an oscilloscope or other measuring or recording apparatus as desired.

The structure of the electron collector 32 and its associated circuitry is illustrated in greater detail in FIG. 2. The collector assembly comprises a grounded shielding enclosure 33 in which are located a collector plate 38, a screen grid 36, and an entrance grid 34. The entrance grid is disposed across an aperture in the front wall of enclosure 33 and is electrically connected thereto. Both the screen grid 36 and the collector plate 38, preferably are sectors of a sphere having a radius of curvature substantially equal to the active length of the electron beam path 21 between the plasma boundary 13 and the collector 32. In one system which has been constructed, and in which the electron beam 21 from accelerator 14 to collector 32 is about 25 centimeters long, a collector plate 38 having a radius of curvature of 20 centimeters has been used. The spherical shape of the collector plate 38 and the screen grid 36 minimizes changes in the electron beam path length which would otherwise result from deflection of the beam. That is, even though the beam may be slightly deflected by longitudinal potential variations in the plasma stream the spherical collector 38 maintains the beam path length constant so that deflection of the electron beam does not alter the beam transit time and does not affect the relative phase of the 30 megacycle signal which is generated by the collector 32. The screen grid 36 is bypassed to ground through a .01 microfarad capacitor 42 so that the screen grid shields the collector plate 38 and prevents stray signals from being picked up by the collector. Accordingly, the only signal picked up on the collector 38 and fed to the amplifier 24 is the 30 megacycle signal generated by intensity modulations of the plasma-exiting beam electrons 22.

Additional passive amplification of the 30 megacycle signal is provided by a tuned circuit comprising distributed capacitance 40 and inductor 46, which is connected to ground through the series combination of a 50 ohm resistor 48 and a .01 microfarad capacitor 50. The tuned circuit comprising inductor 46 and distributed capacitance 40 is tapped at the 50 ohm point and is connected to the center conductor 54 of a coaxial cable 52 which preferably delivers the signal through a blocking capacitor 62 to a similar resonant circuit (not shown) at the input of the amplifier 24.

The method and apparatus of the present invention may be most clearly understood by brief consideration of the theoretical basis on which it depends. It can be shown that a beam of low density but relatively high energy electrons traveling across a portion of the plasma stream 10 will have a transit time dependent on potential variations in the plasma stream. Electric fields parallel to the electron beam accelerate the electrons and cause the transit time to differ from the electron transit time which exists when the plasma is absent. That is, just before ion source 12 is pulsed "ON" the potential is everywhere zero in the region between the boundaries 13 and 15. When the source 12 is turned on and a plasma is present between the boundaries 13 and 15, the potential of that plasma will determine the velocity of electrons which are traversing the same and, hence, will determine the phase difference between the 30 megacycle modulation of the injected electrons **20** and that of the exiting electrons **22**. Comparing the phase of the collected electron beam to that of the modulating signal which is applied to the electron gun **14** enables a detection of transit time variations.

Signal levels at the phase detector **26** should be constant, or at least sufficiently large so that amplitude changes will not give rise to apparent phase shifts.

Once the phase change is measured it can be related to the potential change as follows: let

V_o=Accelerating voltage of the electron beam gun **16**.
dL=An incremental element of the beam path **21**.
dt_1=Electron transit time through dL when the potential is zero along dL.
dt_2=Electron transit time through dL when potential is V(L) along dL.
$dt=dt_1-dt_2$=The difference in transit times through dL due to potential V(L).

$$dt_1=dL/kV_o^{1/2},\ dt_2=dL/k(V_o+V(L))^{1/2} \quad (1)$$

$$dt=dt_1-dt_2=\frac{dL}{kV_o^{1/2}}\left[\frac{[1+(V(L)/V_o)]^{1/2}-1}{[1+(V(L)/V_o)]^{1/2}}\right] \quad (2)$$

The electron transit time change along the whole beam path **21** is:

$$\Delta t=\frac{1}{kV_o^{1/2}}\int_0^L\frac{[1+(V(L)/V_o)]^{1/2}-1}{[1+(V(L)/V_o)]^{1/2}}dL \quad (3)$$

Note that there is implicit in this expression the assumption that the length of the flight path $0 \rightarrow L$ remains constant. If $V(L) \ll V_o$, then

$$[1+(V(L)/V_o)]^{1/2} \cong 1+(V(L)/2V_o) \quad (4)$$

and

$$\Delta t \cong \frac{1}{kV_o^{1/2}}\int_0^L\frac{V(L)}{2V_o+V(L)}dL \approx \frac{1}{2kV_o^{3/2}}\int_0^L V(L)dL \quad (5)$$

The time change Δt is, of course, directly proportional to the phase change. Using 900 volt electrons, a potential of two volts along a 10 centimeter path will produce a Δt of about 1×10^{-11} seconds.

To provide for adequate time resolution of transient potential events, it is desirable that the frequency of the modulating signal from generator **29** should be at least about an order of magnitude higher than the highest frequency component of the plasma potential variations which is to be resolved. By using a 30 megacycle modulating frequency, a plasma potential variation having a duration of one microsecond is averaged over 30 cycles of the modulating signal. To provide wide bandwidth in the system the tuned circuit comprising inductor **46** and the distributed capacitance **40**, preferably has its Q limited to about 10. With all tuned circuits being so arranged to provide a frequency response of about three megacycles, the limiting factor in the transient response time of the system of FIG. 1 is the RC time constant of an integrating circuit (not shown) in the output of the phase detector. In that integrating circuit a compromise between high sensitivity and fast response time is necessary. A large plate resistor in the output of the phase detector will produce more output voltage and, hence, higher sensitivity but with a slower rise time in the response of the system to rapid variations in plasma potential. The requirements and end purposes of a particular application of the method and apparatus of the present invention will determine the RC time constant of the phase detector circuit which is used in a given instance.

There are several ways in which erroneous phase information can be impressed on the 30 megacycle signal and consequently appear in the phase detector output.

If 30 megacycle pickup were present anywhere in the circuitry, this pickup signal would be added vectorially to the 30 megacycle signal at collector **32**. The resultant would be a signal with a phase intermediate between the two. When the collector signal changes phase, the resultant vector would also change phase, but not by the same amount. Furthermore, any amplitude change in either the pickup or collector **32** signal would change the phase of their vector sum. Thus, we have found that high frequency pickup must be kept as small as possible.

To minimize such pickup, the collector **38** preferably is enclosed in the grounded shielding enclosure **33** having a high-mesh-number entrance grid **34**. We have found that 100 mesh screen having .001 inch wires may be used for both the entrance grid **34** and the screen grid **36**. The presence of entrance grid **34** introduces the problem of secondary electrons originating either on the entrance grids **34** or the collector plate **38**. If the collector is biased positively to limit its production of secondaries, it will pull in secondaries which are generated on the entrance grid. Because of the transit times involved, such secondary electrons may carry different phase information from that of the primary beam. Also, their number will change as the beam is moved over the entrance grid because of unavoidable differences in the secondary emission yield at different points on the grid **34**. When the collector plate **38** is biased negatively, the same type of problem exists with respect to electrons leaving the plate. To overcome the foregoing difficulty, screen grid **36** is provided between the collector plate **38** and the entrance grid. Screen grid **36** performs a further beneficial function. Since a charge approaching a plate induces a current at the plate before it actually arrives, the signal carried by the charge will have a slow rise time. Placing the screen grid **36** close to the plate **38** lessens this rise time by shielding the plate **38** from such induction.

Screen grid **36** is biased at minus 90 volts by connection to ground through a voltage source **58** to suppress secondary electrons originating at the entrance grid **34**. The collector plate is biased at plus 45 volts, and secondaries from the screen grid **36** are pulled across the small separation distance to the plate **38** with a short transit time. Those secondaries which originate on the collector plate itself go out only a short distance before returning.

While the present invention has been shown in one form only, it will be obvious to those skilled in the art that it is not so limited but is susceptible of various changes and modifications without departing from the spirit and scope thereof.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method for measuring potential gradients within a stream of ionized particles, comprising:
   - projecting a beam of electrons transversely through said stream;
   - modulating said beam at a frequency which is higher than the frequency of the potential gradient variations in said stream which are to be detected; and
   - measuring the phase difference between the modulation of the projected beam and that of the electron beam subsequent to passage through said stream to provide a signal which varies as a function of the stream potential relative to that of the electron beam source.

2. A method for measuring the distribution of potentials within a plasma comprising the steps of:
   - causing a stream of relatively high energy electrons to traverse a portion of the plasma;
   - modulating said stream with a modulation frequency which is relatively high in comparison to the fre-

quency of the potential variations in said plasma which are to be resolved;

collecting at least a portion of the electrons forming said stream subsequent to their traversal of said portion of the plasma;

utilizing the collected electrons to generate a signal, at the modulation frequency, which is phase delayed to an extent dependent on said transit time; and

measuring the phase difference between said signal and the input modulation to provide an output signal indicative of intraplasma potential variations.

3. A method for measuring potential gradients within a stream of ionized particles, comprising:

projecting a beam of electrons transversely through said stream;

modulating said beam at a high frequency compared to the frequency of the potential gradient variations in said stream which are to be resolved; and

measuring the phase difference between the modulations of the projected beam and the electron beam subsequent to passage through said stream to provide a signal which varies as a function of accelerative potential gradients within said stream.

4. A method for measuring the electric potential at a selected point in a plasma environment comprising:

projecting a beam of relatively high velocity electrically charged particles through a portion of the plasma;

intensity modulating said beam at a frequency such that the modulation period is of the same order of time magnitude as the time required for said charged particles to traverse said portion of the plasma;

collecting a portion of the electrons which constitute said beam after the same has traversed said portion of the plasma;

measuring the phase relation between the modulation of the projected beam and the modulation of the collected electrons to provide an electron time of flight indicative signal, from which potential variations within the plasma may be detected.

5. The method of measuring rapid fluctuations of potential within a plasma which comprises:

causing a beam of electrons to traverse a portion of said plasma;

modulating said beam with a frequency such that the modulation period is approximately an order of magnitude shorter than the fluctuations which are desired to be detected and measured;

collecting a portion of the electrons which constitute said beam after the same have traversed said portion of the plasma;

utilizing the collected electrons to derive a signal, at the modulation frequency, which is variably phase shifted in response to variations in the intraplasma transit time of the beam electrons; and

measuring the phase of said signal to provide an output signal indicative of the rate and magnitude of fluctuations in accelerative potential gradients which may occur within said plasma.

6. In an apparatus for measuring potential variations within a stream of ionized particles:

a high velocity cathode ray beam source;

means for directing the cathode ray beam transversely through a portion of said stream of ionized particles;

a radio frequency signal generator coupled to modulate said beam at a relatively high frequency compared to the frequency of the potential variations in said stream which are to be resolved;

means for collecting at least a portion of said beam electrons and generating signals corresponding to the modulation of said beam; and

a phase detector for measuring and indicating the phase difference between said signals and a phase reference signal.

7. The apparatus of claim **6** in which said cathode ray beam is modulated at a frequency of the order of 30 Mc./second and in which said phase detector is constructed and arranged to have an integrating time constant of the order of 2×10^{-7} seconds so that variations in the transit time of beam electrons as small as 2×10^{-11} seconds are measurable.

8. The apparatus of claim **6** in which said cathode ray beam is modulated at a frequency of about 30 Mc./second so that the modulation period is about 3.3×10^{-8} seconds, and in which the transmit time required for beam electrons to cross said stream is about 1.5 to 2.0×10^{-8} seconds so that the beam electrons traverse the stream of ionized particles in a time period which is shorter than the period of the beam modulation.

9. The apparatus of claim **6** in which the means for receiving and collecting the beam electrons comprises a substantially semi-spherical collector plate having a radius of curvature approximately equal to the active length of the cathode ray beam so that slight variations in beam deflection angle are prohibited from causing variations in the beam source-to-collector-plate transit time of the beam electrons.

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